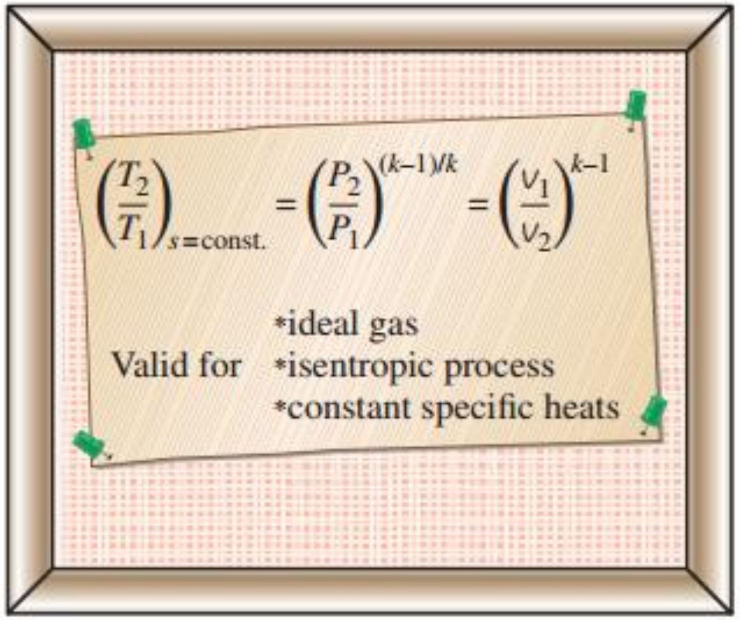
Ch06: Using Entropy
Lecture 21



$$\left(\frac{T_2}{T_1}\right)_{s=\text{const.}} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

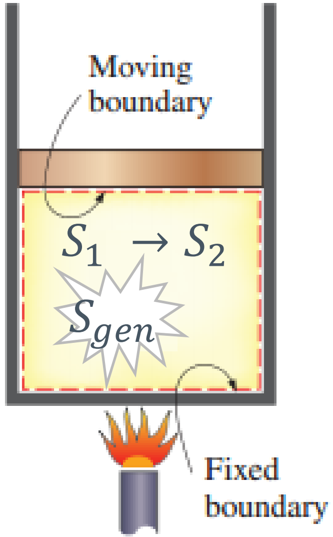
Valid for
*ideal gas
*isentropic process
*constant specific heats

Instructor: Ammar Gwesha
ME210 Thermodynamics I
Spring 2017

Today’s Outlines (6.10 → 6.13)

- Review
- Steady-State Entropy Rate Balance for CVs
  - Special Cases
- Isentropic Process
  - Pure Substance
  - Incompressible Substance
  - Ideal Gas
- Isentropic Efficiency

Entropy Balance (2nd Law) for Closed Systems

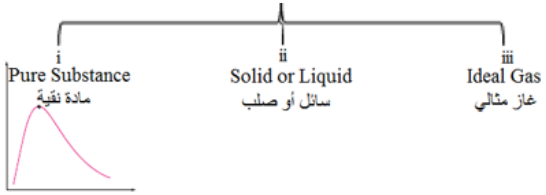


Summary:

Entropy Balance (2nd Law) for a Closed System:

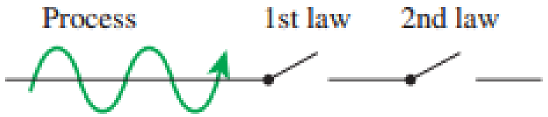
$$\boxed{S_2 - S_1} = \boxed{\int_1^2 \left(\frac{\delta Q}{T}\right)_b} + \boxed{S_{gen,1-2}}$$

Entropy Change inside the system
التغير في الانتروبي داخل المنظومة
{+,-,0}



Net Amount of Entropy Transfer by Heat across the system boundary
صافي الانتروبي المنتقلة عبر حدود المنظومة بسبب الحرارة
{+,-,0}

Entropy Produced inside the system due to irreversibilities
الانتروبي المتولدة أو المنتجة داخل داخل المنظومة
نتيجة لوجود مصادر اللاانعكاسية
{always ≥0}



Summary

2nd Law

Cycle

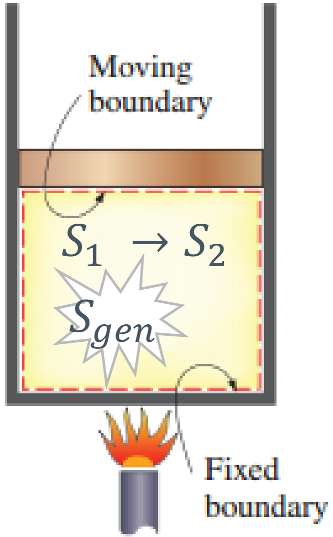
Process

For a Cyclic Process

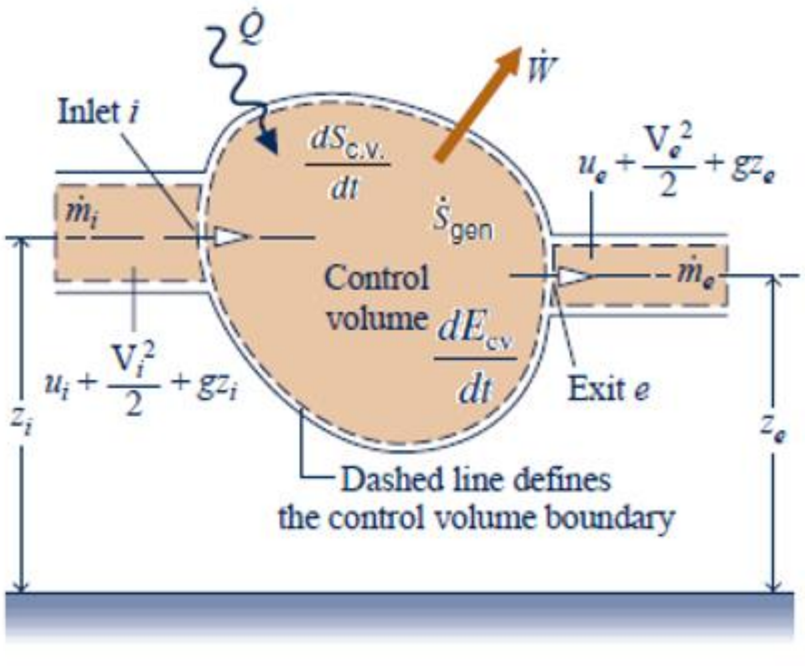
$$\oint \left(\frac{\delta Q}{T}\right)_b = -S_{gen,cycle}$$

For a Closed System,

$$S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_b + S_{gen,1-2}$$



Rate Balances for CVs


$\dot{Q}$
$\dot{W}$
Inlet i
$\frac{dS_{\text{c.v.}}}{dt}$
$u_e + \frac{V_e^2}{2} + gz_e$
$\dot{m}_i$
$\dot{S}_{\text{gen}}$
Control volume
$\frac{dE_{\text{cv}}}{dt}$
$\dot{m}_e$
$u_i + \frac{V_i^2}{2} + gz_i$
Exit e
z_i
z_e
Dashed line defines the control volume boundary

- Mass Rate Balance:

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

- Energy Rate Balance:

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

- Entropy Rate Balance:

$$\underbrace{\frac{dS_{cv}}{dt}}_{\substack{\text{rate of entropy} \\ \text{change within cv}}} = \underbrace{\sum_{c.s,\, j} \frac{\dot{Q}_{cv,\, j}}{T_j}}_{\substack{\text{rate of entropy} \\ \text{transfer by heat}}} + \underbrace{\sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e}_{\substack{\text{rate of entropy} \\ \text{transfer by mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{rate of entropy} \\ \text{generated inside cv}}}$$

SSSF Rate Balances for CVs

- Mass Rate Balance:

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e$$

- Energy Rate Balance:

$$\dot{Q}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) = \dot{W}_{cv} + \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

- Entropy Rate Balance:

$$\underbrace{\sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i}_{\substack{\text{rate of entropy} \\ \text{transfer by mass}}} = \underbrace{\sum_{c.s,\, j} \frac{\dot{Q}_{cv,\, j}}{T_j}}_{\substack{\text{rate of entropy} \\ \text{transfer by heat}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{rate of entropy} \\ \text{generated inside cv}}}$$

$$\sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = \sum_{c.s,\, j} \frac{\dot{Q}_{cv,\, j}}{T_j} + \dot{S}_{gen}$$

Steady-State Entropy Rate Balance for CVs

- Special Cases:

(1) Single flow (one-inlet & one-exit)

$$\dot{m}(s_e - s_i) = \sum_{c.s,\, j} \frac{\dot{Q}_{cv,\, j}}{T_j} + \dot{S}_{gen}$$

{+,0,-} {+,0,-} {0,+}

$$\Rightarrow s_e = s_i + \frac{1}{\dot{m}}\left(\sum_{c.s,\, j} \frac{\dot{Q}_{cv,\, j}}{T_j}\right) + \frac{\dot{S}_{gen}}{\dot{m}}$$

(2) Single flow (one-inlet & one-exit) + Adiabatic CV

$$\dot{m}(s_e - s_i) = 0 + \dot{S}_{gen}$$

{+,0} {+,0}

$$\sum_{e}\dot{m}_e s_e - \sum_{i}\dot{m}_i s_i = \sum_{c.s,\,j}\frac{\dot{Q}_{cv,\,j}}{T_j} + \dot{S}_{gen}$$

Steady-State Entropy Rate Balance for CVs

- Special Cases:

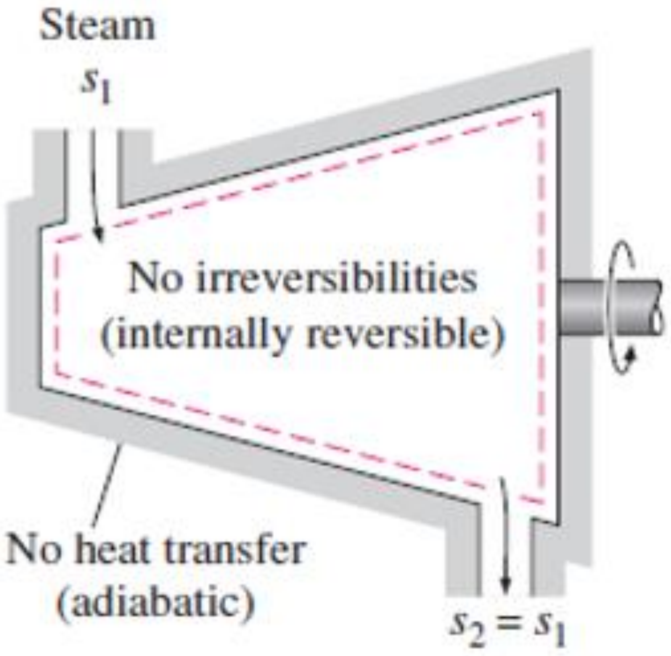
(3) Reversible + Adiabatic = isentropic process

$$\sum_{e}\dot{m}_e s_e = \sum_{i}\dot{m}_i s_i$$

(4) Single flow + isentropic

$$\dot{m}(s_e - s_i) = \sum_{c.s,\,j}\frac{\dot{Q}_{cv,\,j}}{T_j} + \dot{S}_{gen} = 0 + 0$$

$$s_e = s_i$$



$$\sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = \sum_{c.s,\, j} \frac{\dot{Q}_{cv,\, j}}{T_j} + \dot{S}_{gen}$$

Steady-State Entropy Rate Balance for CVs

- Special Cases:

(5) Single flow + Int. Reversible + Isothermal process

$$\dot{m}(s_e - s_i) = \frac{\dot{Q}_{cv}}{T}$$

$$\left(\frac{\dot{Q}_{cv}}{\dot{m}}\right)_{\substack{\text{int}\\ rev}} = T(s_e - s_i)$$

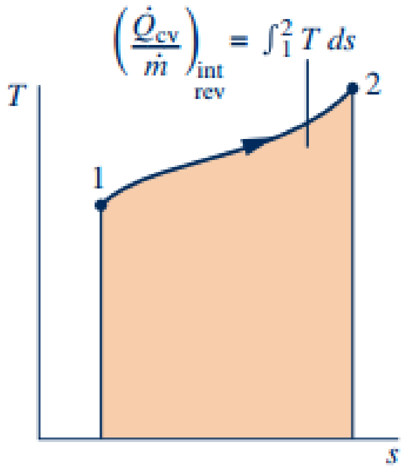


Fig. 6.13 Area representation of heat transfer for an internally reversible flow process.

Example

- للتربين البخاري المبين بالشكل، افترض أن عملية تمدد المادة النقية عبر التربين المعزول انعكاسية داخليا. استنتج علاقة تربط بين انتروبي مدخل التربين ومخرجيه.

Mass Rate Balance: $\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \rightarrow (1)$

Entropy Rate Balance:

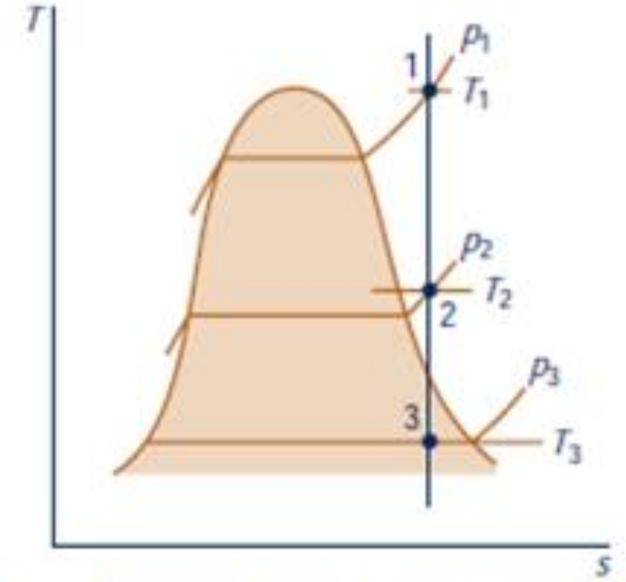
$$\sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = \sum_{c.s,\, j} \frac{\dot{Q}_{cv,\, j}}{T_j} + \dot{S}_{gen}$$

$$\sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = 0 + 0$$

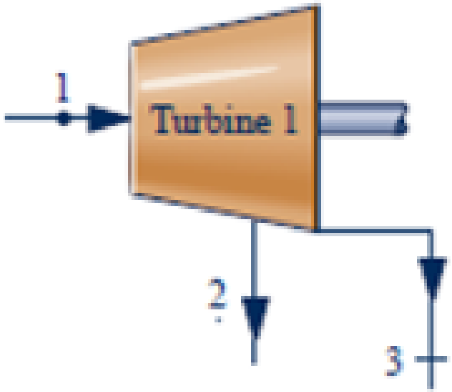
$$\dot{m}_1 s_1 = \dot{m}_2 s_2 + \dot{m}_3 s_3 \rightarrow (2)$$

$$(\dot{m}_2 + \dot{m}_3) s_1 = \dot{m}_2 s_2 + \dot{m}_3 s_3$$

$$\dot{m}_2 s_1 + \dot{m}_3 s_1 = \dot{m}_2 s_2 + \dot{m}_3 s_3 \quad \Rightarrow s_1 = s_2 = s_3$$



T–s diagram showing states having the same value of specific entropy.



Work in Int Rev SSSF Processes

Assumptions: SSSF, Single flow, int rev process

$$0 = \dot{Q}_{cv} - \underbrace{\dot{W}_{cv}}_{nonflow} + \sum_i \dot{m}_i (h_i + \underbrace{\frac{V_i^2}{2} + gz_i}_{\div 1000 \to kJ/kg}) - \sum_e \dot{m}_e (h_e + \underbrace{\frac{V_e^2}{2} + gz_e}_{\div 1000 \to kJ/kg})$$

$$\dot{W}_{\substack{\text{int}\\ rev}} = \dot{Q}_{\substack{\text{int}\\ rev}} + \dot{m}\{(h_i - h_e) + (\frac{V_i^2 - V_e^2}{2}) + g(z_i - z_e)\}$$

$$\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)_{\substack{\text{int}\\ rev}} = \left(\frac{\dot{Q}_{cv}}{\dot{m}}\right)_{\substack{\text{int}\\ rev}} + (h_i - h_e) + (\frac{V_i^2 - V_e^2}{2}) + g(z_i - z_e)$$

$$\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)_{\substack{\text{int}\\ rev}} = \int_i^e Tds + (h_i - h_e) + (\frac{V_i^2 - V_e^2}{2}) + g(z_i - z_e)$$

Work in Int Rev SSSF Processes

Assumption: SSSF, Single flow, int rev process

$$\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)_{\substack{\text{int}\\ rev}} = \underline{\int_i^e Tds + (h_i - h_e)} + (\frac{V_i^2 - V_e^2}{2}) + g(z_i - z_e)$$

Recall $Tds = dh - vdP$

$$\int_i^e Tds = (h_e - h_i) - \int_i^e vdP \Rightarrow \int_i^e Tds + (h_i - h_e) = -\int_i^e vdP$$

$$\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)_{\substack{\text{int}\\ rev}} = -\int_i^e vdP + (\frac{V_i^2 - V_i^2}{2}) + g(z_i - z_e)$$

Work in Int Rev SSSF Processes

Assumptions:

SSSF, Single flow, int rev process & no Δke and Δpe

$$\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)_{\substack{\text{int}\\ rev}} = -\int_i^e vdP \qquad\qquad (\Delta ke \approx \Delta pe \approx 0)$$

هذه العلاقة (reversible steady-state work) صالحة لـ:

أجهزة التدفق المستقر سواء المنتجة لقدرة مثل التربينات، أو المستهلكة لقدرة مثل الضواغط والمضخات.

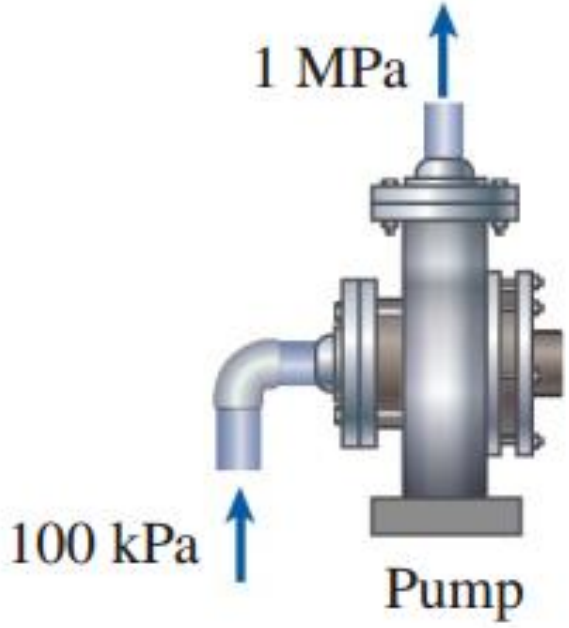
Work in Int Rev SSSF Processes

حالة خاصة:

عند مرور سائل عبر مضخة (باعتبارها جهاز تدفق مستقر انعكاسي) فإن الشغل اللازم لتشغيل المضخة

$$v_{liquid} \approx C$$

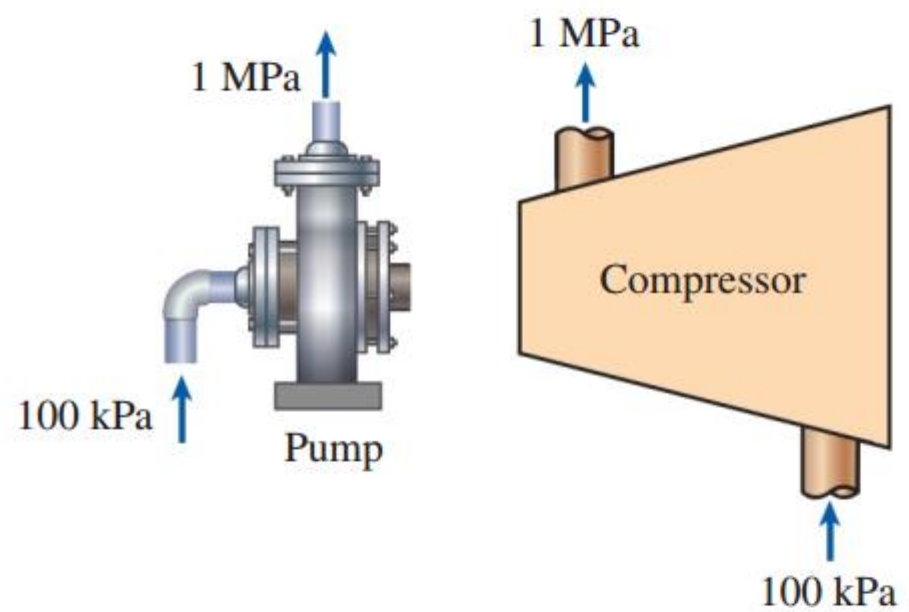
$$\left(\frac{\dot{W}_{pump}}{\dot{m}}\right)_{\substack{\text{int}\\ rev}} = -\int_i^e v\,dP \approx -v(P_e - P_i)$$



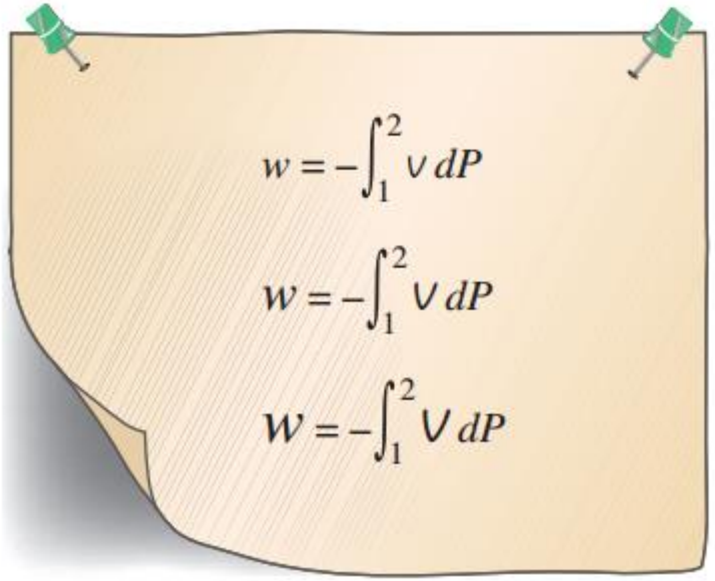
Work in Int Rev SSSF Processes

سؤال للمناقشة:

إذا علمت أن مقدار الارتقاع في الضغط متساو (same pressure rise) في الجهازين، أي من الجهازين تتوقع أن يستهلك قدرة (لكل وحدة كتلة مارة عبر الجهاز) أكبر لتشغيله ؟



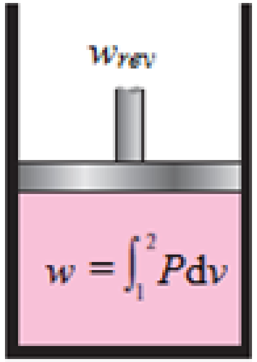
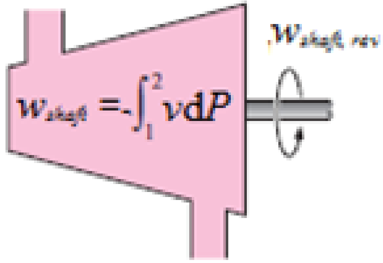
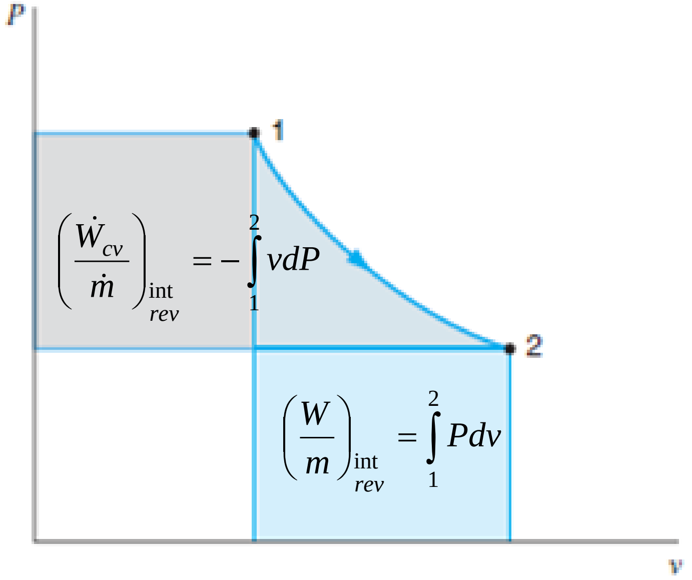
$$v_{liquid} << v_{vap\ or\ gas}$$



$$w = -\int_1^2 v\, dP$$

$$w = -\int_1^2 V\, dP$$

$$W = -\int_1^2 V\, dP$$

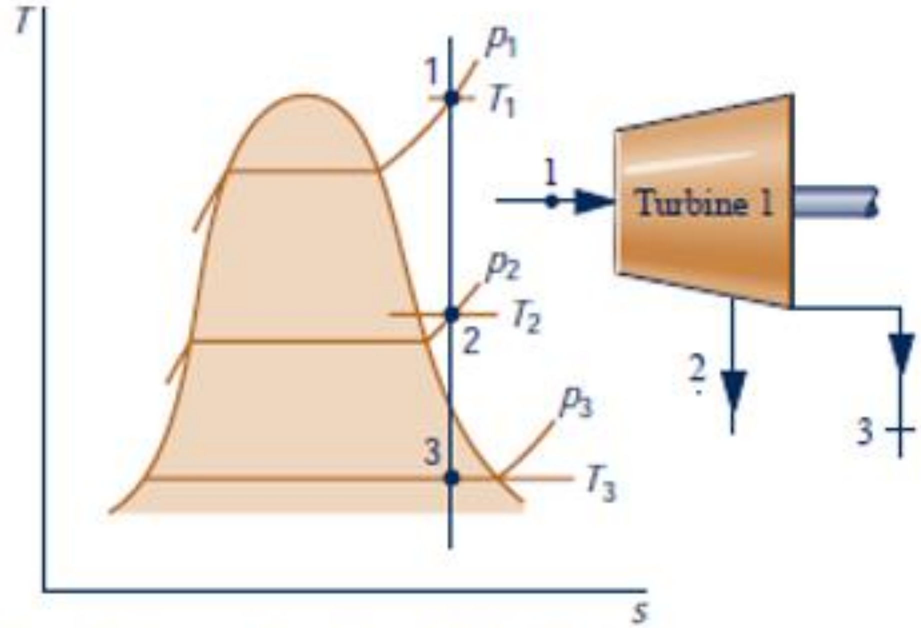
System	Closed System (c.m)	Open System (c.v.)
Assumptions	simple compressible substance	no KE/PE changes
Reversible Work, [kJ/kg]	boundary work = $\int_1^2 P\,d\,v$  special case: $w_{bound} = 0$; isochoric process	shaft work = $-\int_i^e v\,dP$  special case: $w_{shaft} = 0$; isobaric process
Graphical Representation	 P 1 2 v $\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)_{\substack{int\\rev}} = -\int_1^2 vdP$ $\left(\frac{W}{m}\right)_{\substack{int\\rev}} = \int_1^2 Pdv$	

Isentropic Process $\Delta s = 0$

- $\Delta s = 0$
  - Pure Substance
  - Liquid or Solid
  - Ideal Gas

Isentropic Process $\Delta s = 0$

- Pure Substance, $s_1 = s_2 = s_3$
- Given: P_1, P_2, P_3 & T_1. For an isentropic turbine, Find: T_2 & T_3



T–s diagram showing states having the same value of specific entropy.

Isentropic Process $\Delta s = 0$

- **سؤال للمناقشة:**

إذا خضع سائل إلى عملية أيزنتروبية ماذا تتوقع أن يحصل لدرجة الحرارة السائل (↓ أو ↑ أو =)؟

وضح إجابتك مستعينا بعلاقة التغير في الانتروبي

$$\Delta s = \; c ln(\frac{T_2}{T_1})$$

Isentropic Process $\Delta s = 0$

- **Ideal Gases (Is ΔT large or small??)**

(1) Using Constant Specific Heats

$$\Delta s_{ideal\ gas} = (s_2 - s_1) = \begin{cases} c_{p,\,ave} \ln\left(\dfrac{T_2}{T_1}\right) - R\ln\left(\dfrac{P_2}{P_1}\right) \\ c_{v,\,ave} \ln\left(\dfrac{T_2}{T_1}\right) + R\ln\left(\dfrac{v_2}{v_1}\right) \\ c_{p,\,ave} \ln\left(\dfrac{v_2}{v_1}\right) + c_{v,\,ave} \ln\left(\dfrac{P_2}{P_1}\right) \end{cases}$$

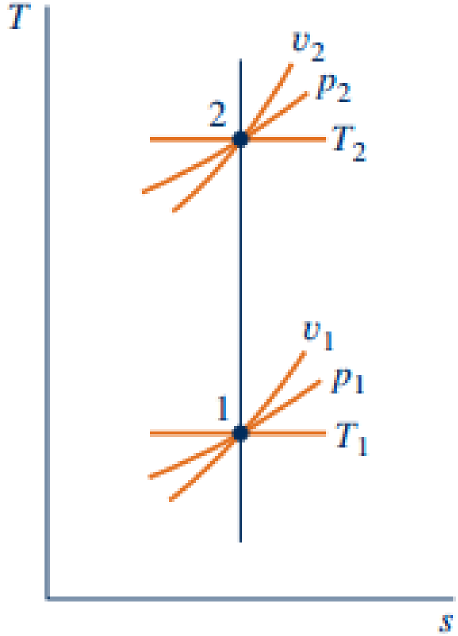


Fig. 6.9 Two states of an ideal gas where $s_2 = s_1$.

By setting,

$$\Delta s_{ideal\ gas} = (s_2 - s_1) = 0$$

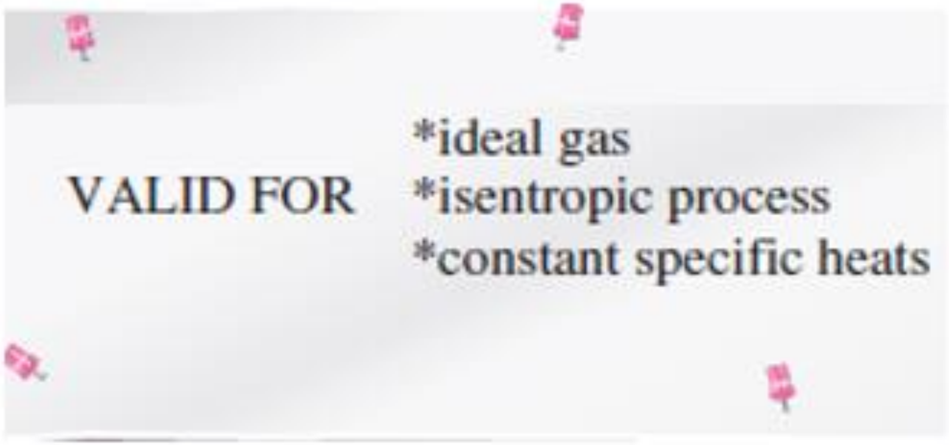
Isentropic Process $\Delta s = 0$

- **Ideal Gases (Is ΔT large or small??)**

(1) Using Constant Specific Heats

By setting, $\Delta s_{ideal\ gas} = (s_2 - s_1) = 0$

$$\left(\frac{T_2}{T_1}\right)_{s=cons} = \left(\frac{P_2}{P_1}\right)^{\frac{(k-1)}{k}} = \left(\frac{v_1}{v_2}\right)^{k-1}$$



VALID FOR
*ideal gas
*isentropic process
*constant specific heats

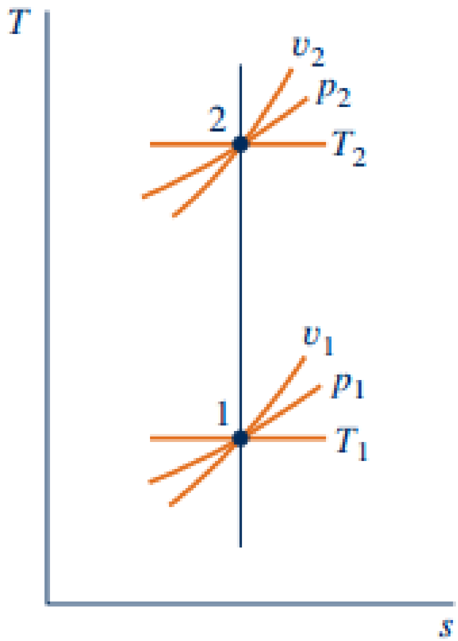


Fig. 6.9 Two states of an ideal gas where $s_2 = s_1$.

Isentropic Process $\Delta s = 0$

- **Ideal Gases IG (Is ΔT large or small??)**

(2) Using Variable Specific Heats (IG Tables)

$$\Delta s_{ideal\ gas} = s_2(T_2, P_2) - s_1(T_1, P_1) = s^0_{T_2} - s^0_{T_1} - R\ln\left(\frac{P_2}{P_1}\right)$$

$$\Delta s_{ideal\ gas} = (s_2 - s_1) = 0$$

$$s_2(T_2, P_2) - s_1(T_1, P_1) = s^0_{T_2} - s^0_{T_1} - R\ln\left(\frac{P_2}{P_1}\right) = 0$$

$$\underbrace{s^0_{T_2} - s^0_{T_1} - R\ln\left(\frac{P_2}{P_1}\right) = 0}_{\substack{It\ involves\ 4\ properties \\ T_1,\ T_2,\ P_1\ \&\ P_2}}$$

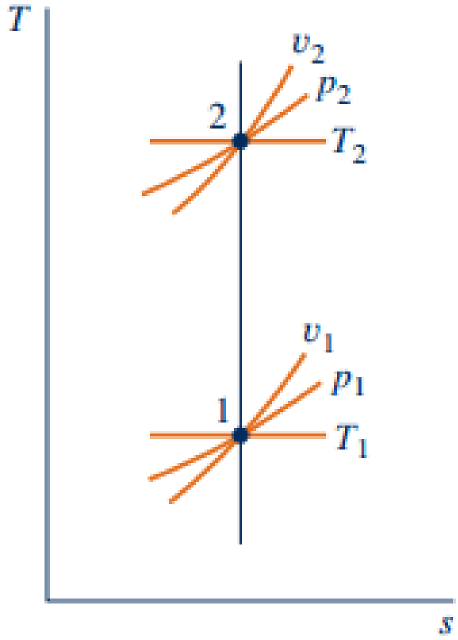


Fig. 6.9 Two states of an ideal gas where $s_2 = s_1$.

Isentropic Process $\Delta s = 0$

- **Ideal Gases IG (Is ΔT large or small??)**

(2) Using Variable Specific Heats (IG Tables)

$$\underbrace{s^0_{T_2} - s^0_{T_1} - R\ln\left(\frac{P_2}{P_1}\right) = 0}_{\substack{\textit{It involves 4 properties} \\ T_1,\, T_2,\, P_1 \,\&\, P_2}}$$

Given: P_1, P_2, & T_1, Find: T_2

$$s^0_{T_2} = s^0_{T_1} + R\ln\left(\frac{P_2}{P_1}\right)$$

Given: P_1, T_2, & T_1, Find: P_2

$$\frac{P_2}{P_1} = \exp\left(\frac{s^0_{T_2} - s^0_{T_1}}{R}\right) = \frac{\exp\left(s^0_{T_2}/R\right)}{\exp\left(s^0_{T_1}/R\right)}$$

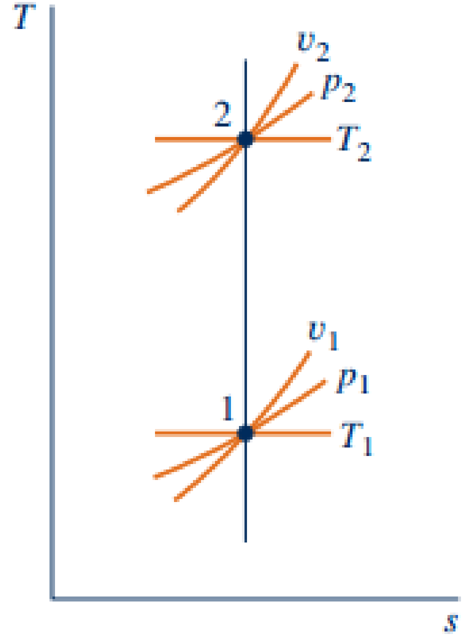
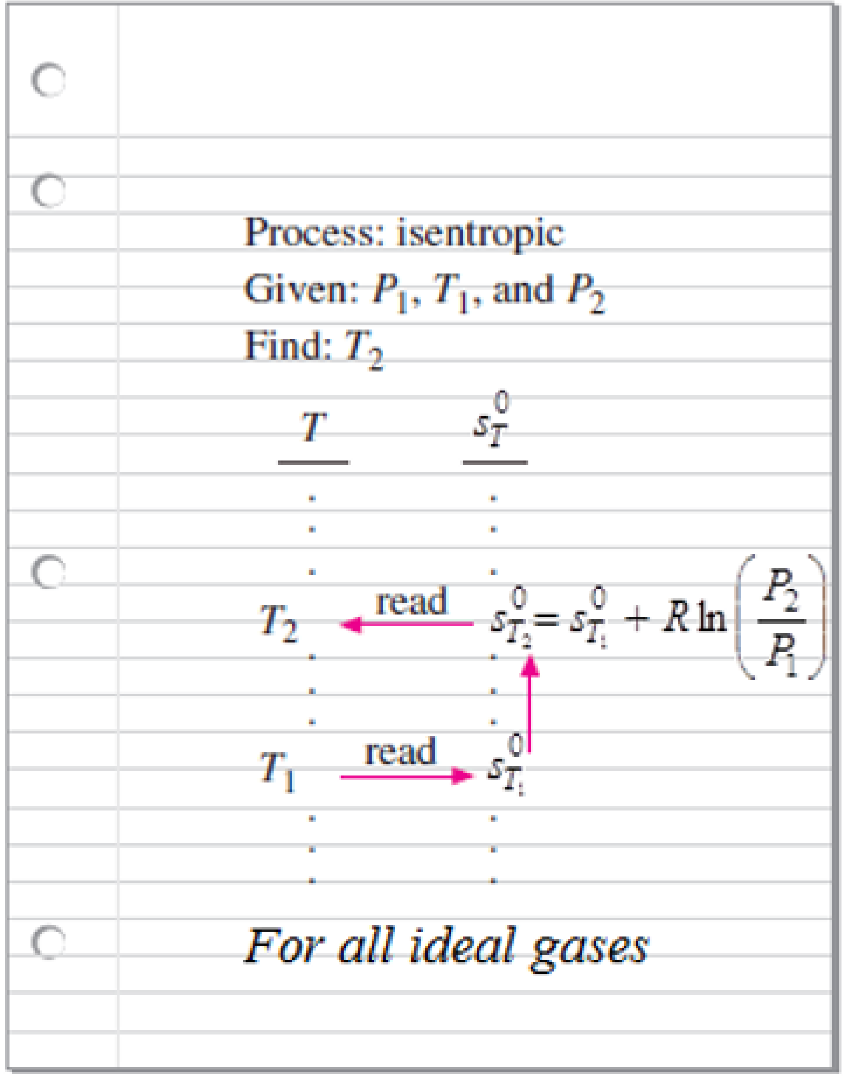


Fig. 6.9 Two states of an ideal gas where $s_2 = s_1$.



Process: isentropic

Given: P_1, T_1, and P_2

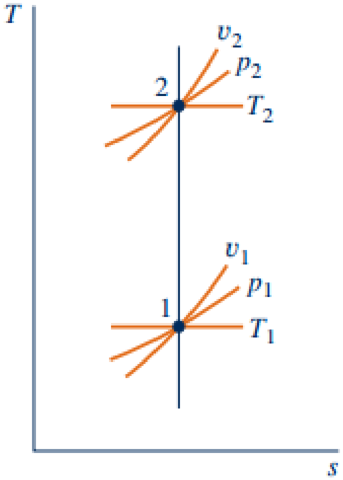
Find: T_2

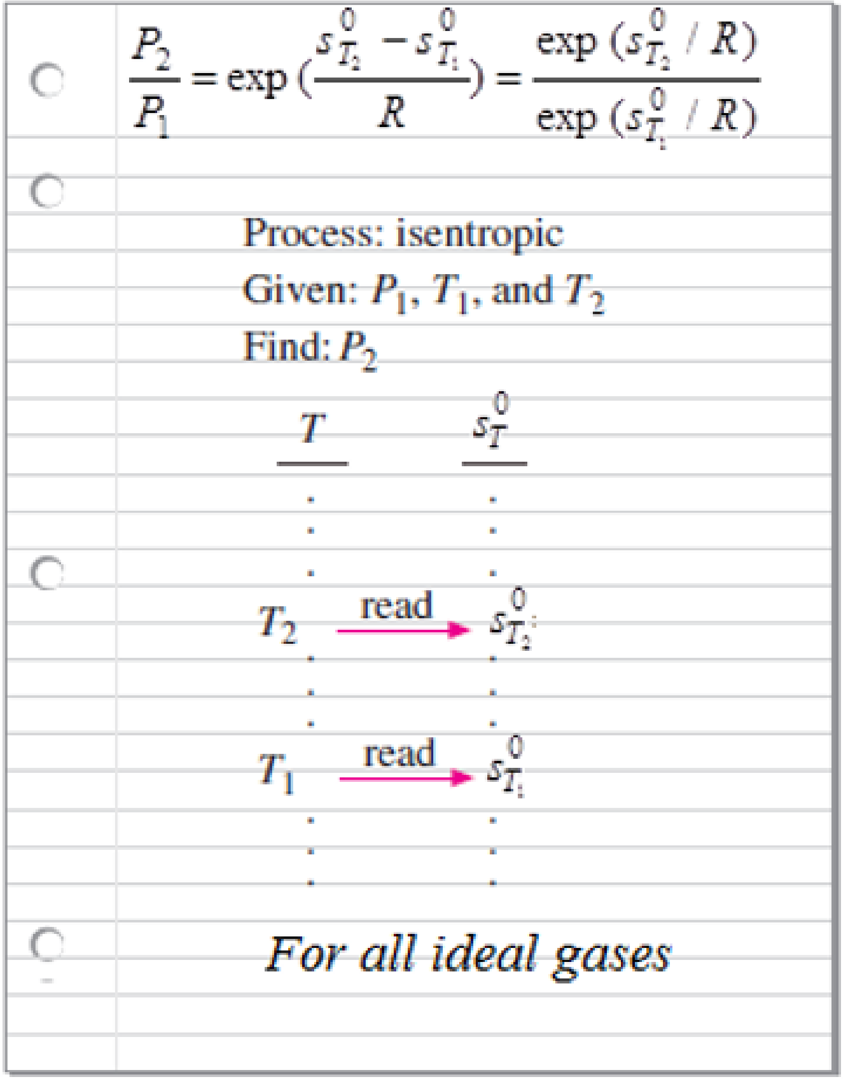
$T \qquad s_T^0$

$$T_2 \xleftarrow{\text{read}} s^0_{T_2} = s^0_{T_1} + R\ln\left(\frac{P_2}{P_1}\right)$$

$$T_1 \xrightarrow{\text{read}} s^0_{T_1}$$

For all ideal gases





$$\frac{P_2}{P_1} = \exp\left(\frac{s^0_{T_2} - s^0_{T_1}}{R}\right) = \frac{\exp(s^0_{T_2}/R)}{\exp(s^0_{T_1}/R)}$$

Process: isentropic

Given: P_1, T_1, and T_2

Find: P_2

$T \qquad s_T^0$

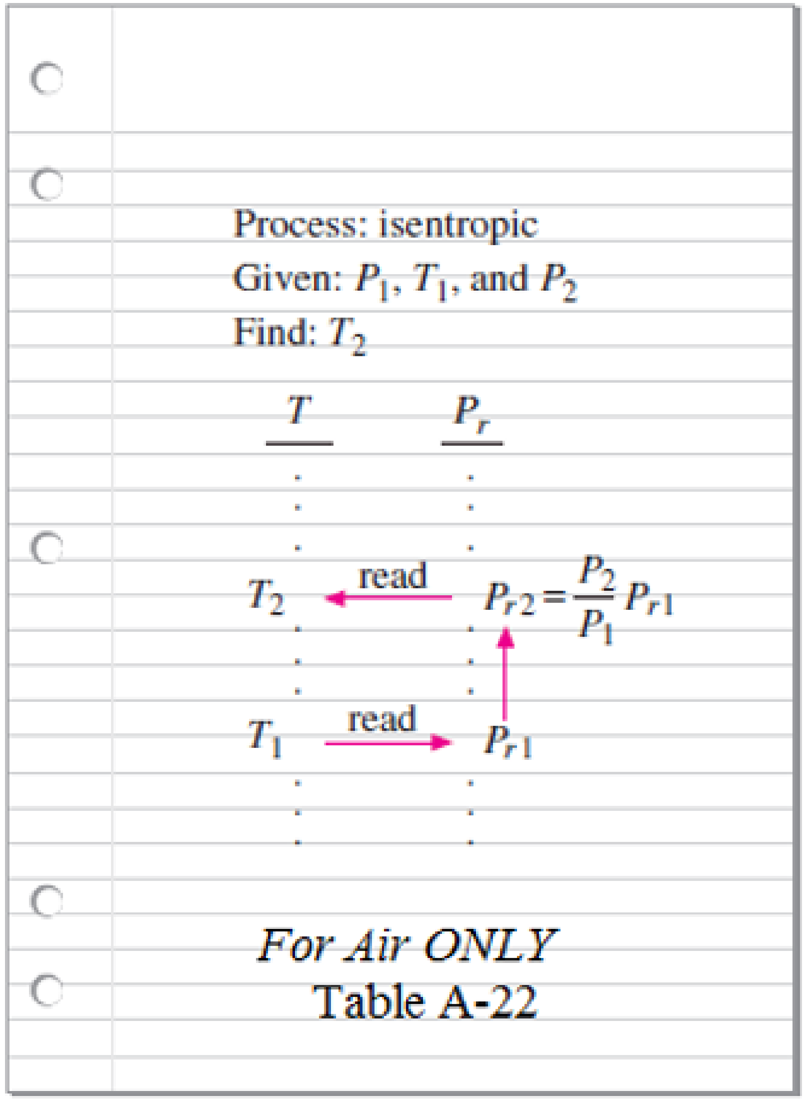
$$T_2 \xrightarrow{\text{read}} s^0_{T_2}$$

$$T_1 \xrightarrow{\text{read}} s^0_{T_1}$$

For all ideal gases

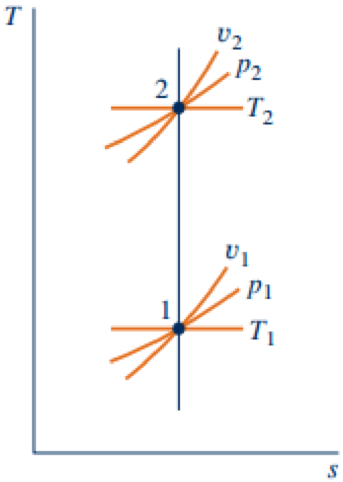
$$\frac{P_2}{P_1} = \frac{\exp\left(s^0_{T_2} / R\right)}{\exp\left(s^0_{T_1} / R\right)} = \frac{P_{r_{T2}}}{P_{r_{T1}}}$$

$$\frac{v_2}{v_1} = \frac{v_{r_{T2}}}{v_{r_{T1}}}$$

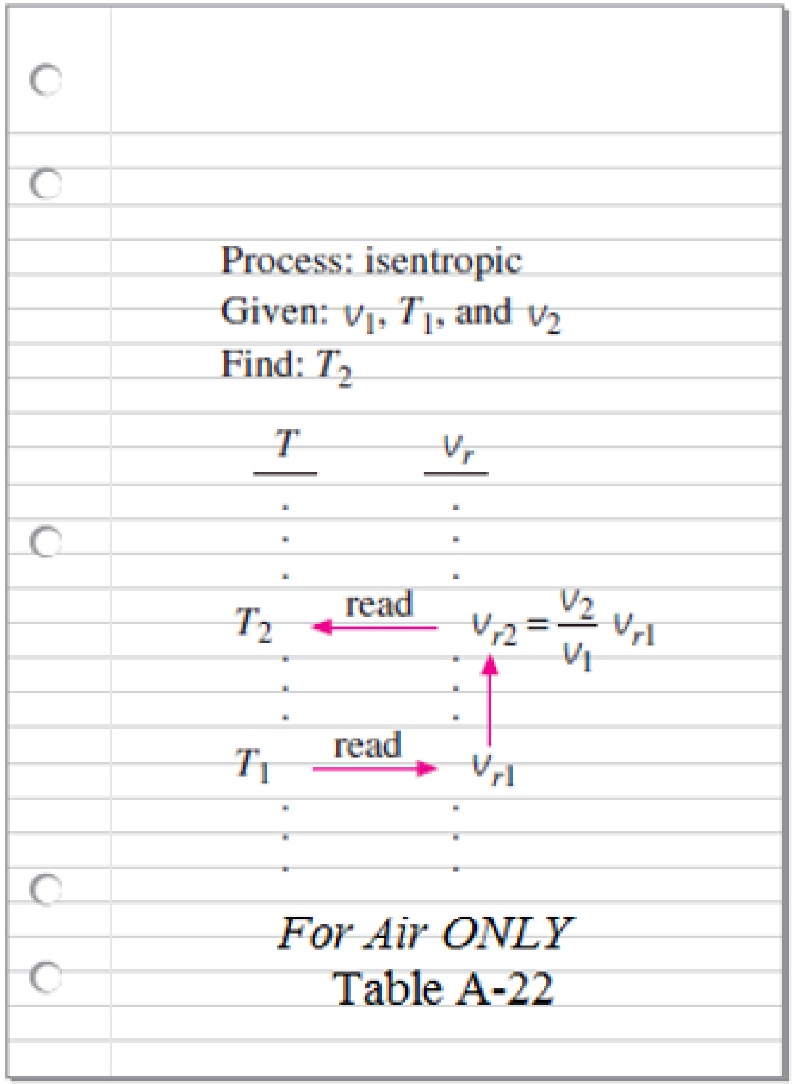


Process: isentropic
Given: P_1, T_1, and P_2
Find: T_2

For Air ONLY
Table A-22



$$P_r \neq \frac{P}{P_{cr}}$$

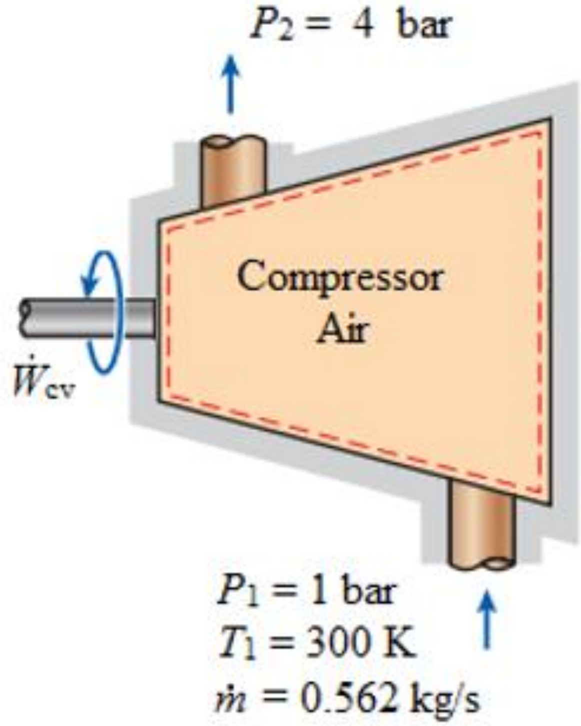


Process: isentropic
Given: v_1, T_1, and v_2
Find: T_2

For Air ONLY
Table A-22

Example (1)

- يتدفق هواء سلوكه مثالي عبر ضاغط يشتغل تحت ظروف مستقرة. بافتراض أن عملية الانضغاط أيزونتروبية، فاحسب درجة حرارة خروج الهواء من الضاغط مرة باستخدام نسبة سعة حرارة نوعية ثابتة k=1.4، ومرة متغيرة. وارسم مخطط T-s للعملية.



Example (1)

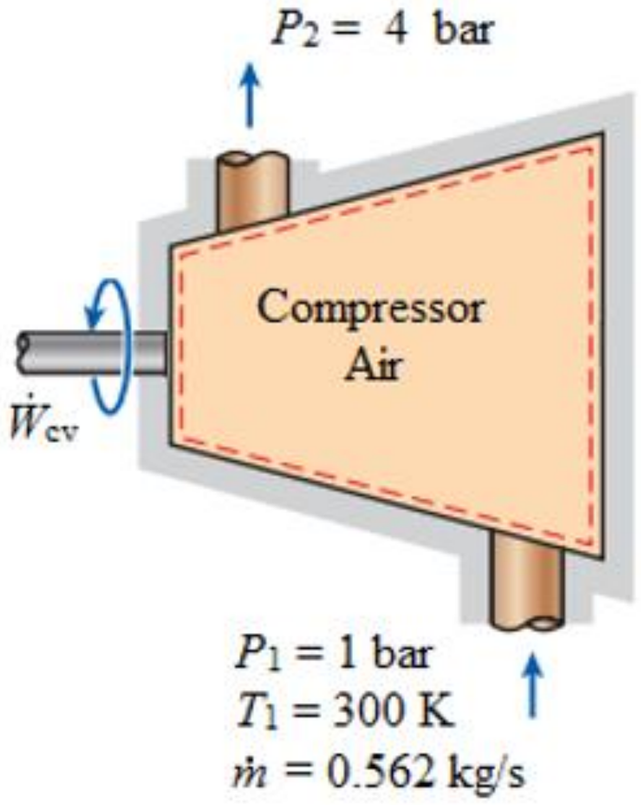
- الإجابة

- Using Constant Specific Heats

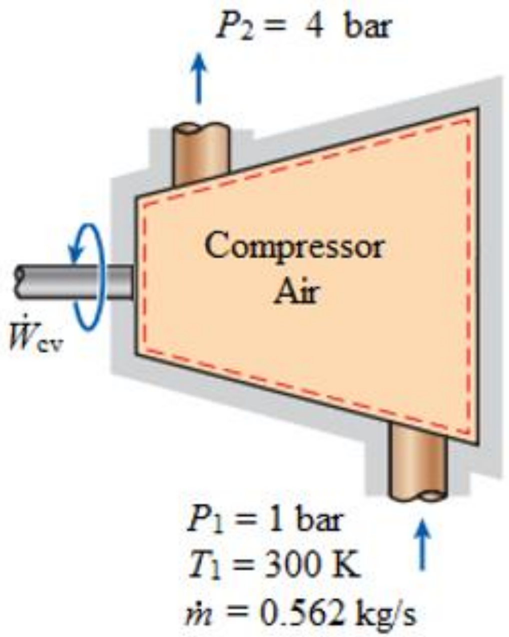
$$\left(\frac{T_2}{T_1}\right)_{s=c} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$$

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} \Rightarrow T_{2s} = 300\left(\frac{400}{100}\right)^{(1.4-1)/1.4}$$

$$T_{2s} = 445.8\ \text{K}$$



Example (1)



- الإجابة

- Using Variable Specific Heats

$$T_1 = 300\text{ K} \xrightarrow{Table\ A\text{–}22} \text{Pr}_1 = 1.386$$

$$\frac{P_2}{P_1} = \left(\frac{\text{Pr}_2}{\text{Pr}_1}\right)_{s=c} \quad \Rightarrow \text{Pr}_{2s} = \text{Pr}_1 \frac{P_2}{P_1}$$

$$\text{Pr}_{2s} = \text{Pr}_1 \frac{P_2}{P_1} = 1.386 \times \frac{4}{1} = 5.544$$

$$T_{2s} \approx 445\text{ K}$$

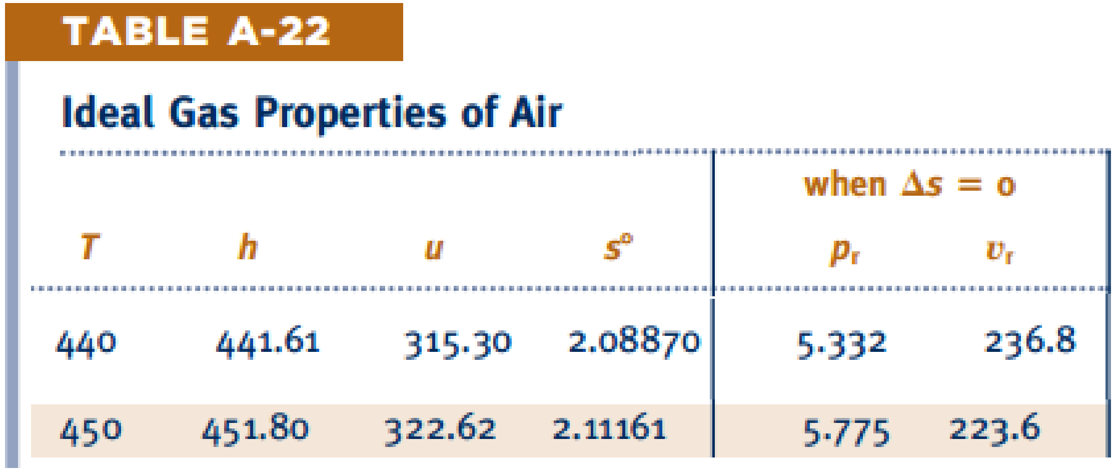


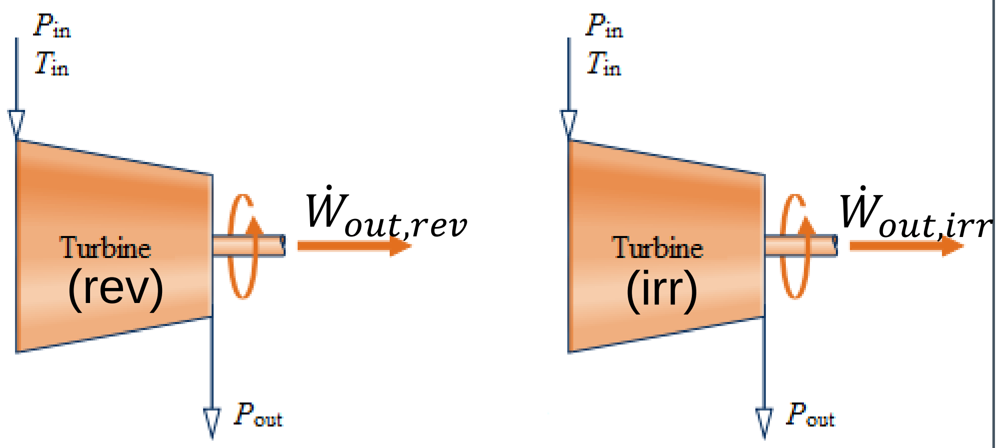
TABLE A-22

Ideal Gas Properties of Air

				when $\Delta s = 0$	
T	h	u	s°	p_r	v_r
440	441.61	315.30	2.08870	5.332	236.8
450	451.80	322.62	2.11161	5.775	223.6

Ideal (Reversible) VS Real (Irreversible)

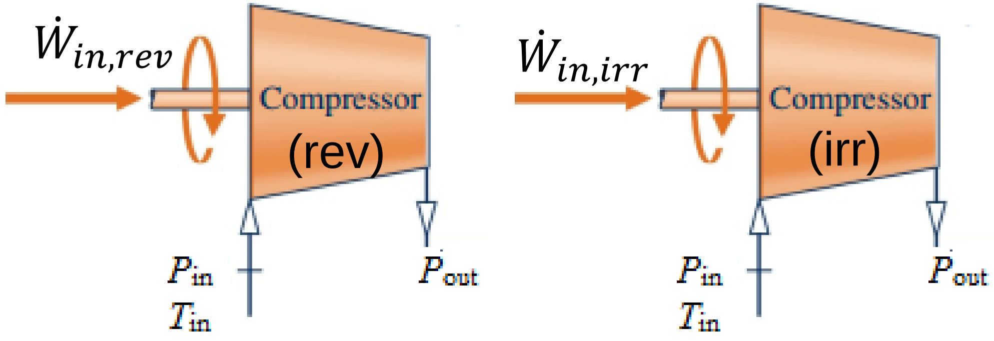
Work-producing device



$$\dot{W}_{out,rev} > \dot{W}_{out,irr}$$

Work-consuming device

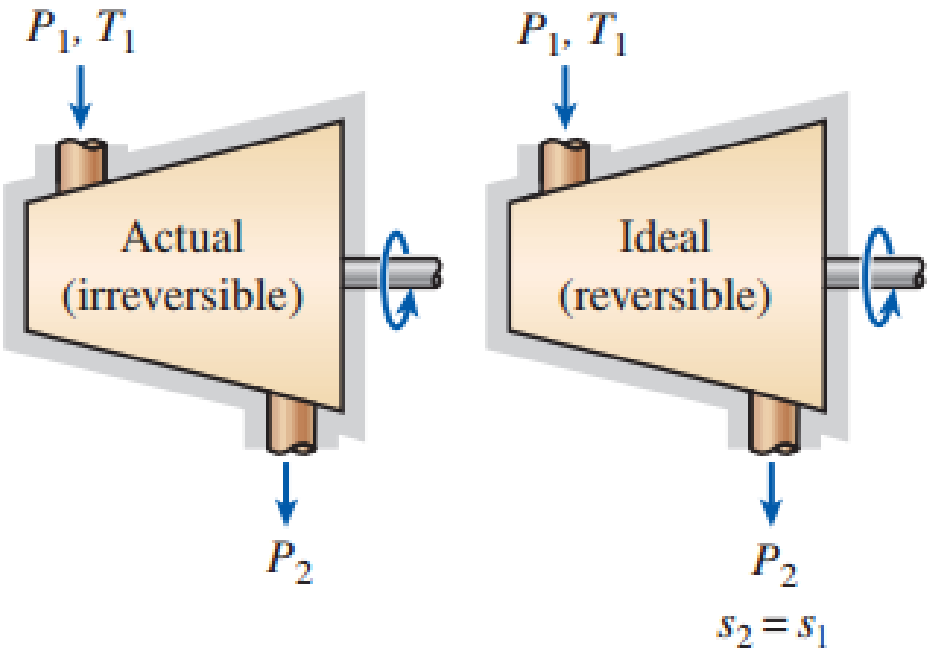
- Ex: compressor, pump, etc



$$\dot{W}_{in,rev} < \dot{W}_{in,irr}$$

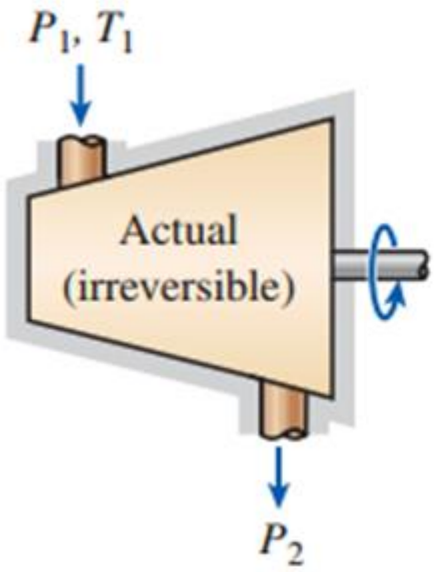
Isentropic Efficiency of SSSF Devices

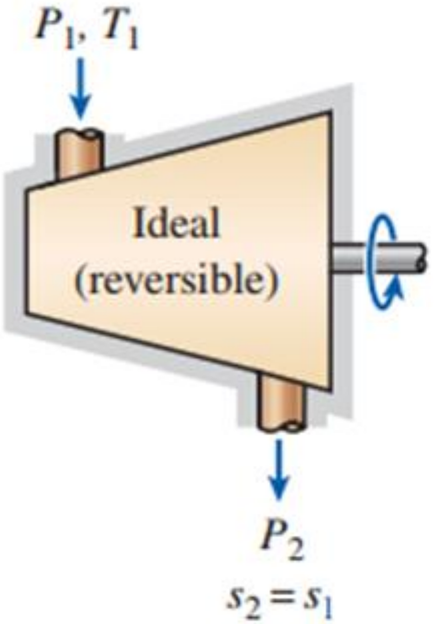
- الكفاءة الأيزنتروبية (isentropic efficiency): هي مقياس لمدى حيود العمليات الفعلية (جهاز التدفق المستقر) عن المثالية (isentropic).
- أسباب الحيود: مصادر اللانعكاسية.



Isentropic Turbine Efficiency

- Assumptions:



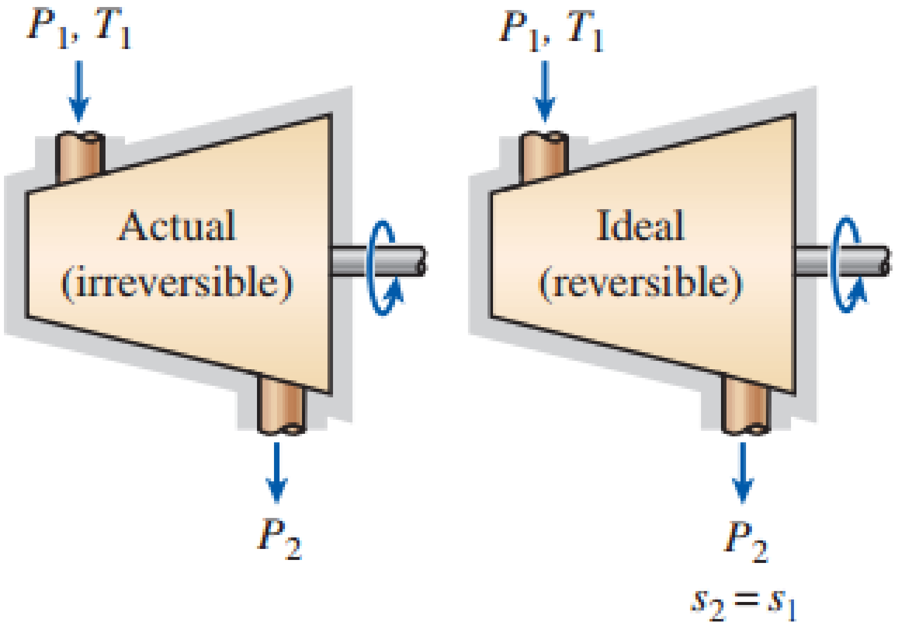


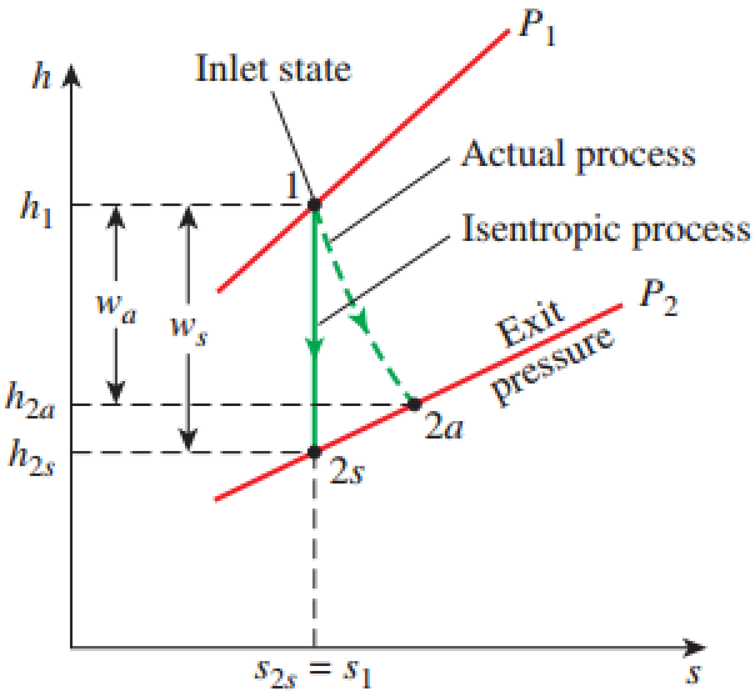
$$\eta_{turbine} = \frac{\dot{W}_a}{\dot{W}_s}$$

① Adiabatic turbine
② ΔKE & ΔPE ~ 0
③ SSSF conditions

Isentropic Turbine Efficiency

- Assumptions:
  - ① Adiabatic turbine
  - ② ΔKE & ΔPE ~ 0
  - ③ SSSF conditions





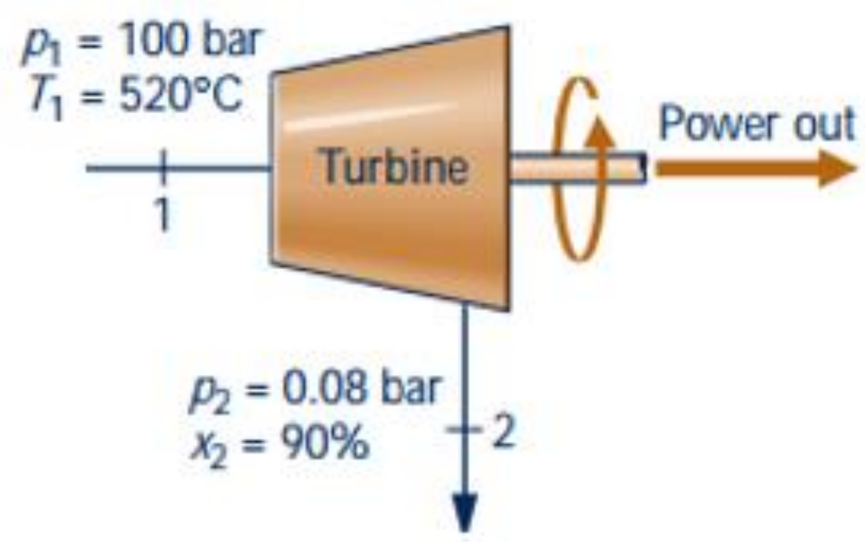
$$\eta_t = \frac{\dot{W}_a}{\dot{W}_s}$$

$$\eta_t = \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$

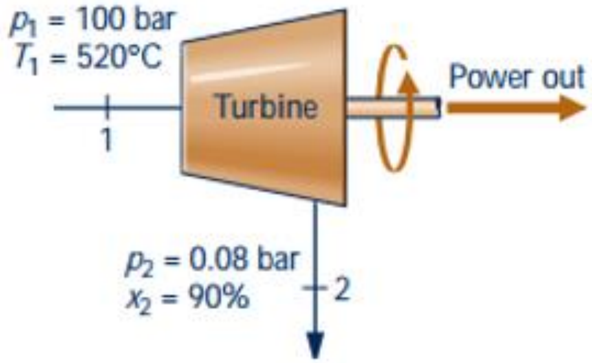
$\eta_t \sim 0.7 – 0.9$

Example

- يتدفق ماء بمعدل 109 kg/s عبر تربين معزول حراريا ويشتغل تحت ظروف مستقرة. بإهمال تأثير طاقتي الحركة والوضع. احسب: (1) قدرة التربين، (2) معدل الانتروبي المتولدة، (3) الكفاءة الايزنتروبية. ارسم مخطط T-s.



Example



Assumptions:

① SSSF Process, ② no $\dot{Q}_{cv}$, ③ no KE & PE effects

Power Produced, $\dot{W}_{cv}$ in MW

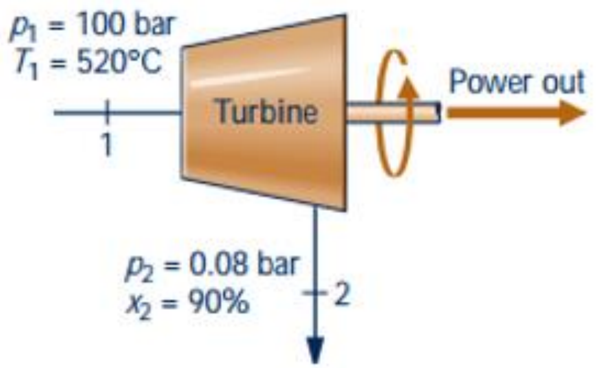
$$\cancel{\dot{Q}_{cv}} + \sum_i \dot{m}_i\left(h_i + \cancel{\frac{V_i^2}{2}} + \cancel{gz_i}\right) = \underbrace{\dot{W}_{cv}}_{nonflow} + \sum_e \dot{m}_e\left(h_e + \cancel{\frac{V_e^2}{2}} + \cancel{gz_e}\right)$$

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$

$$\left.\begin{matrix} T_1 = 520\ ^\circ\text{C} \\ P_1 = 100\ \text{bar}\end{matrix}\right\} \xrightarrow{T_1 > T_{sat\,@\,100\,bar} \Rightarrow \text{Table A-4}} \left\{\begin{matrix} h_1 = 3425.1 \quad \text{kJ/kg} \\ s_1 = 6.6622 \quad \text{kJ/kg.K}\end{matrix}\right.$$

$$\left.\begin{matrix} P_2 = 0.08\ \text{bar} \\ x_2 = 0.9\end{matrix}\right\} \xrightarrow{\text{Table A-3}} \left\{\begin{matrix} h_2 = h_f + x_2(h_g - h_f) = 2336.7 \quad \text{kJ/kg} \\ s_2 = s_f + x_2(s_g - s_f) = 7.4651\ \text{kJ/kg.K}\end{matrix}\right.$$

Example



Power Produced, $\dot{W}_{cv}$ in MW

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$

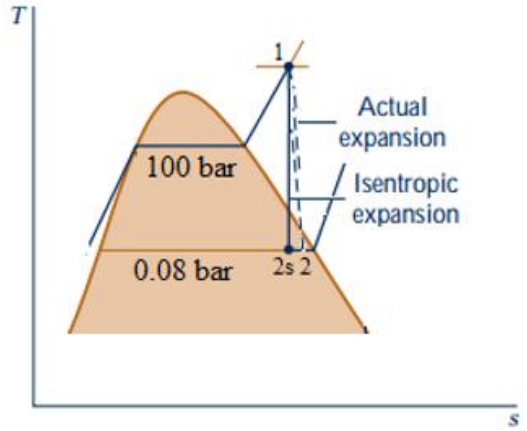
$$= (109\,\frac{\text{kg}}{\text{s}}) \times (3425.1 - 2336.7)\,\frac{\text{kJ}}{\text{kg}} = 118{,}636\,\frac{\text{kJ}}{\text{s}} = 118.64\ \text{MW}$$

Rate of Entropy Production, $\dot{S}_{gen}$ in kW/K

$$\sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i = \sum_{c.s,\ j} \cancel{\frac{\dot{Q}_{cv,\ j}}{T_j}} + \dot{S}_{gen}$$

$$\dot{S}_{gen,turbine} = \dot{m}(s_2 - s_1) = (109\,\frac{\text{kg}}{\text{s}}) \times (7.4651 - 6.6622)\,\frac{\text{kJ}}{\text{kg.K}} = 87.52\,\frac{\text{kW}}{\text{K}}$$

Example



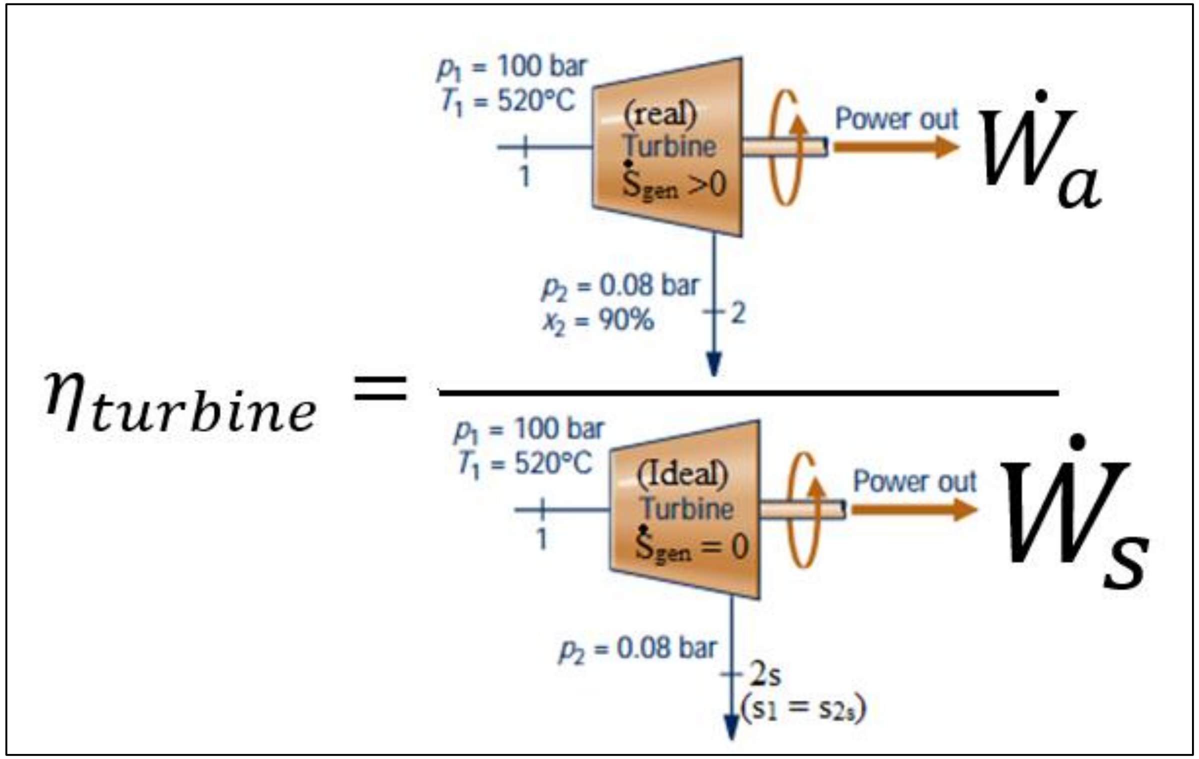
Isentropic Turbine Efficiency

$$\left.\begin{array}{l} P_2 = 0.08\text{ bar} \\ s_{2s} = s_1 \end{array}\right\} \xrightarrow{@\,0.08\text{ bar: } s_f < s_{2s} < s_g \text{ Table A-3}} \begin{cases} x_{2s} = (s_{2s} - s_f)/(s_g - s_f) = 0.795 \\ h_{2s} = h_f + x_{2s}(h_g - h_f) = 2084.3\text{ kJ/kg} \end{cases}$$

$$\eta_{turbine} = \frac{w_a}{w_s} = \frac{h_1 - h_2}{h_1 - h_{2s}}$$

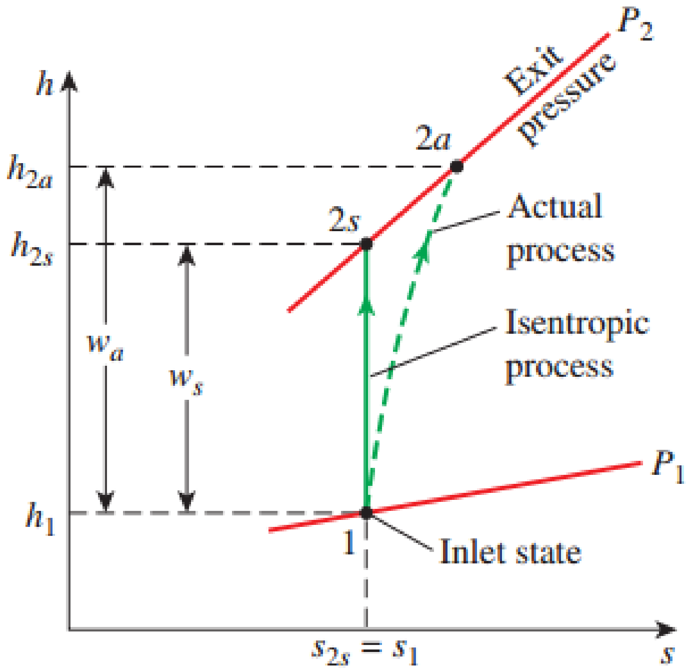
$$\eta_{turbine} = \frac{3425.1 - 23367.7}{3425.1 - 2084.3}$$

$$= 0.812 \ \ (81.2\%)$$



Isentropic Compressor Efficiency

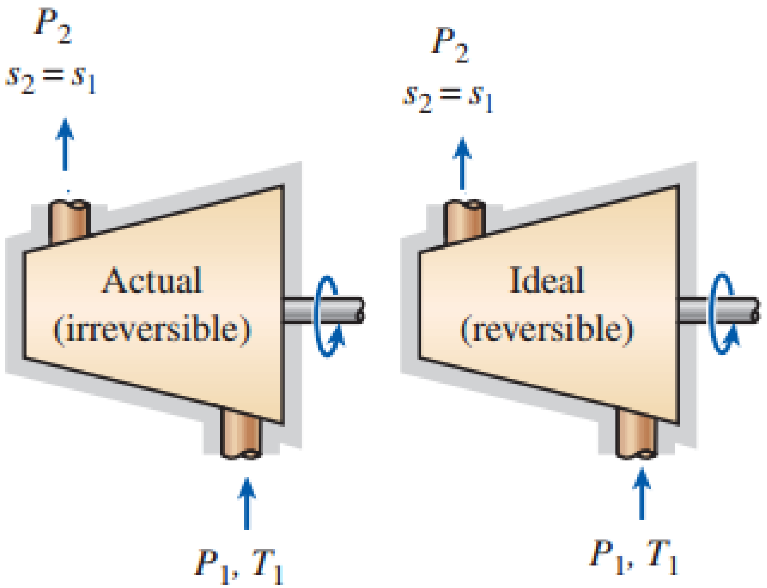
- Assumptions:
  - ① Adiabatic compressor
  - ② ΔKE & ΔPE ~ 0
  - ③ SSSF conditions



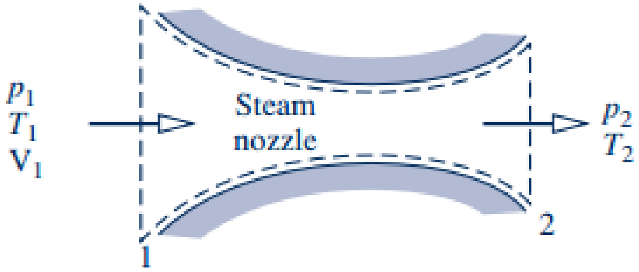
$$\eta_c = \frac{\dot{W}_s}{\dot{W}_a}$$

$$\eta_c = \frac{h_1 - h_{2s}}{h_1 - h_{2a}}$$

η_c ~ 0.75 – 0.85

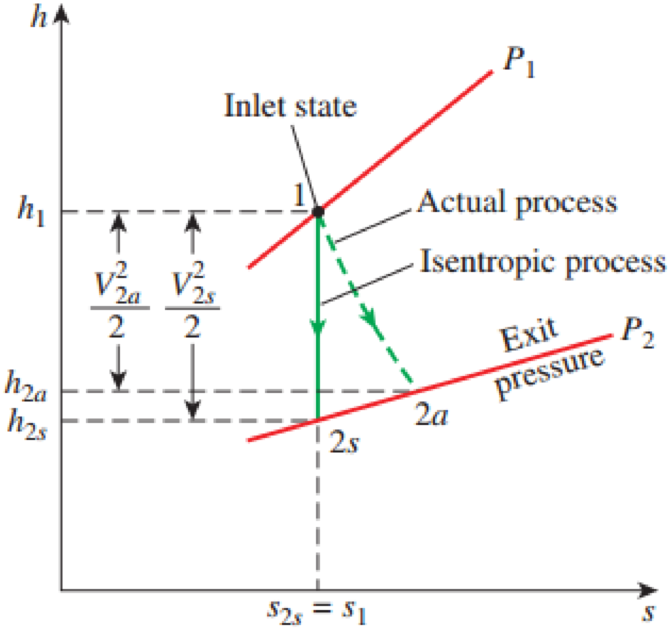


Isentropic Nozzle Efficiency



- Assumptions:
  - ① Adiabatic nozzle
  - ② ΔPE ~ 0
  - ③ SSSF conditions

$$\eta_{nozzle} = \frac{\dot{KE}_{ea}}{\dot{KE}_{es}}$$



$$\eta_{nozzle} = \frac{\left(\frac{V_e^2}{2}\right)_a}{\left(\frac{V_e^2}{2}\right)_s}$$

$$h_i + \frac{V_i^2}{2} + gz_i = h_e + \frac{V_{ea}^2}{2} + gz_e$$

$$h_i + \frac{V_i^2}{2} + gz_i = h_e + \frac{V_{es}^2}{2} + gz_e$$

η_{nozzle} ~ 0.9-95